

High Voltage Converter / Modulator



NC (warm linac):

- Drive 1 ea. 5 MW or 2 ea. 2.5 MW klystrons or 3 ea. 2.5 MW klystrons (reduced power)
 - $5 \text{ MW} / 0.45 = 11.1 \text{ MW peak @ } 140 \text{ kV}$
 - $2 \times (2.5 \text{ MW} / 0.55) = 9.1 \text{ MW peak @ } 130 \text{ kV}$
 - 11 MW peak for 3 2.5 MW klystrons

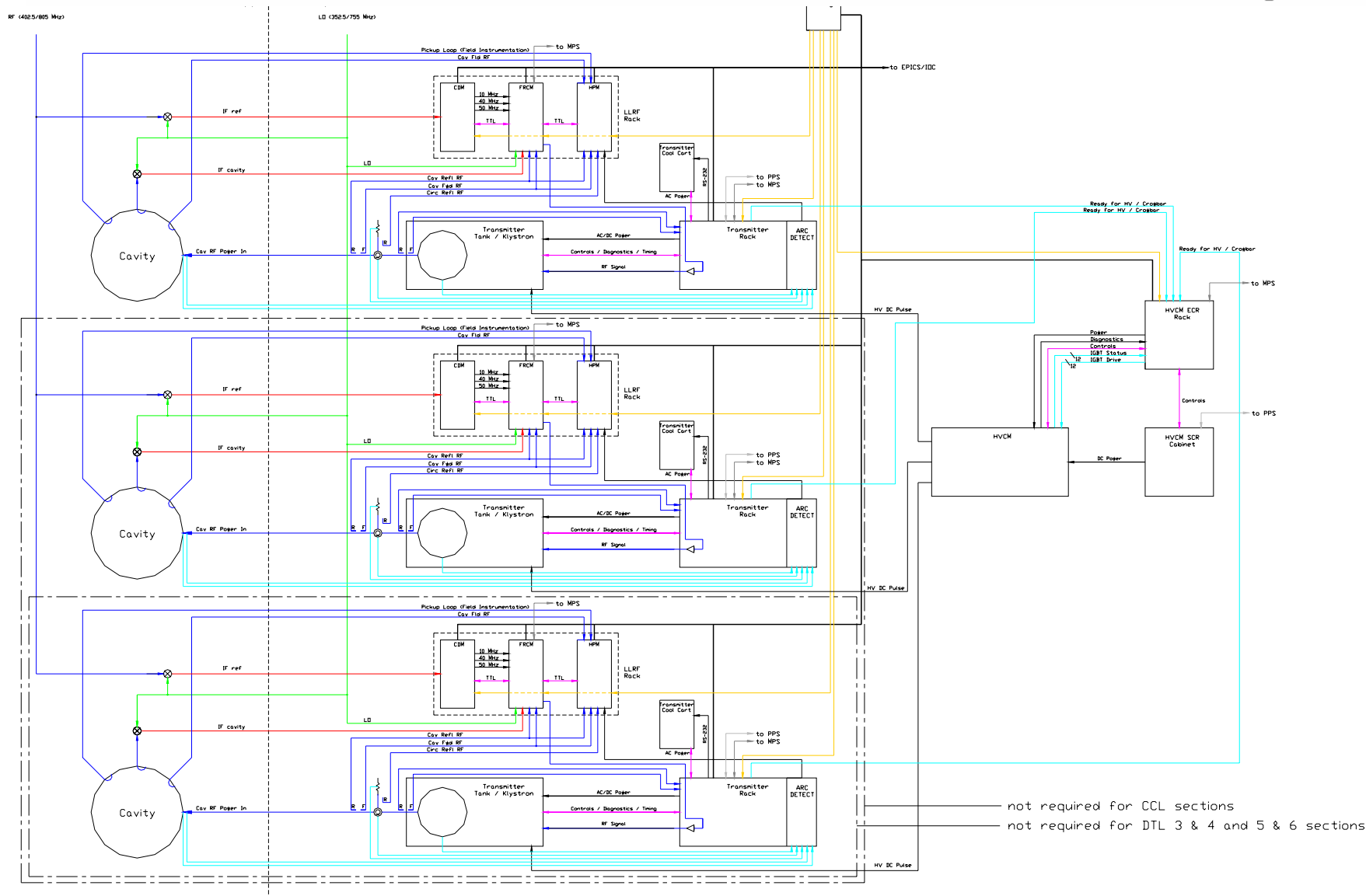
SC (superconducting linac):

- Drive 11 ea. 550 kW klystrons (full power) or 12 ea. 550 kW klystrons (reduced power) @ 69 kV
 - $550 \text{ kW} / 0.63 = 870 \text{ kW}$

All linac:

- 1.4 ms pulse width (allows for cavity fill, modulator risetime, LLRF stabilization period)
- $\pm 1/2\%$ voltage flattop required ($\Rightarrow \pm 1/2^\circ$ phase stability)
- Efficiency $\geq 85\%$ ($\Rightarrow 165 \text{ kW}$ of heat generated)

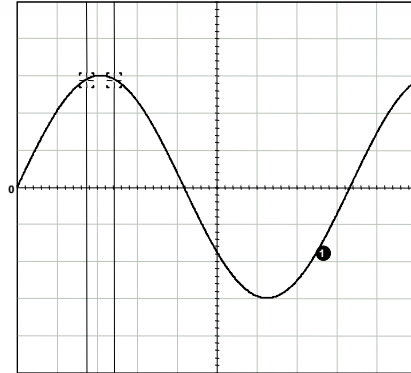
RF Block Diagram



Power Conversion Options



- Use “stepped-up” raw sine wave?
 - ⇒ Flat to $\pm 3.5\%$ over 1.4 ms
 - ⇒ Would require 4.6 MW for 805 MHz NC klystron (5X wasted power)
- Traditional “hard tube” modulator approach?
 - ⇒ Large capacitor bank with high-voltage series switch
 - ⇒ 130 μF required to keep droop at $\leq 1/2\%$
= 1.3 MJ at 140 kV (3 sticks TNT)
 - ⇒ Requires $\sim 25' \times 25' \times 8'$ for capacitors alone
- PFN/Transformer?
 - ⇒ Fixed pulse width, variable involves more switching
 - ⇒ Fast switching required at moderate voltages
 - ⇒ Large $\int V dt$ transformer for > 1 ms pulsewidth

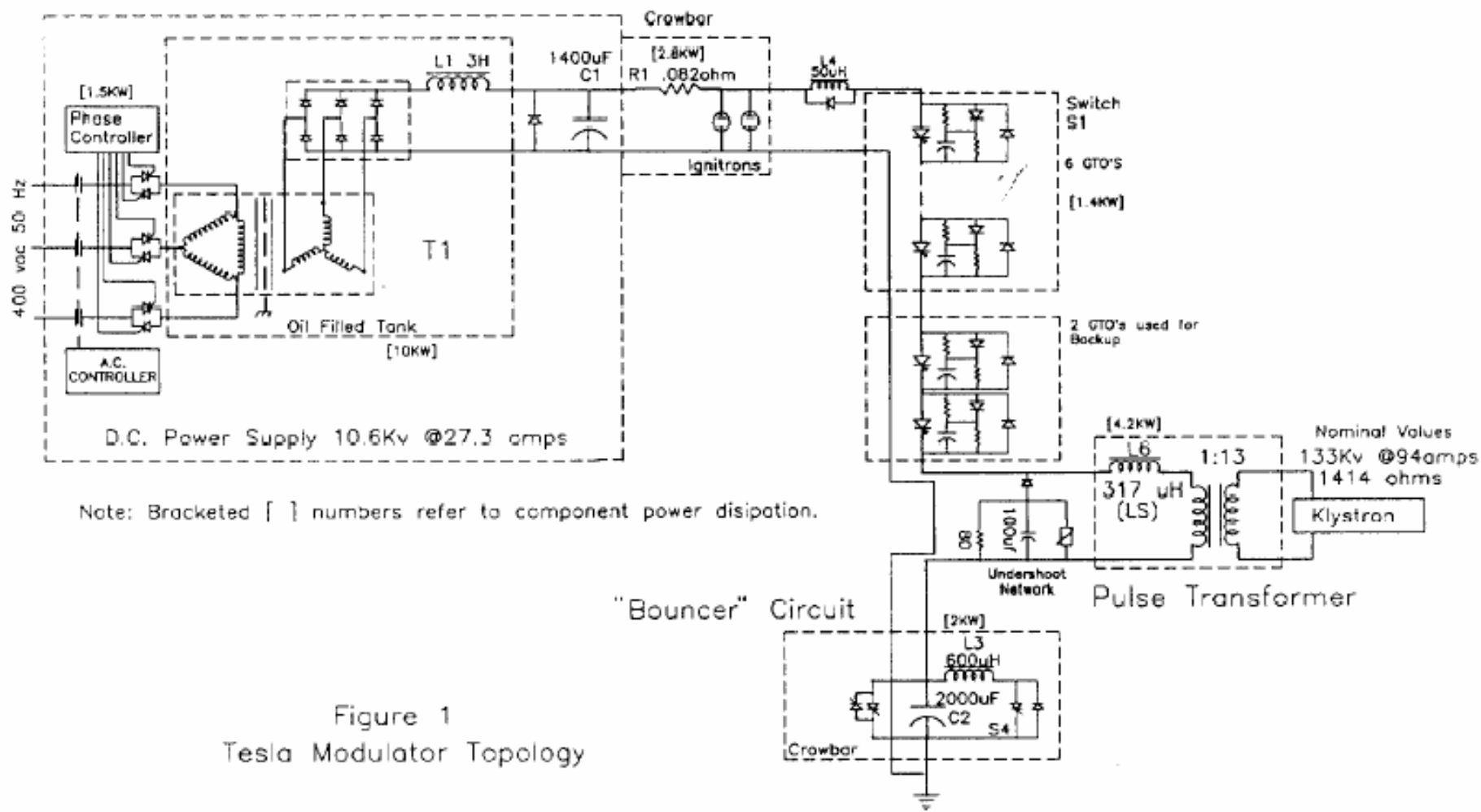


Existing IGBT Modulators



- DTI Modulator
 - Utilizes Series IGBTs to switch HV
 - No regulation possible
 - Requires complex voltage distribution and protection
- Tesla Modulator
 - 1st use of IGBTs in HV application
 - Uses series switches and pulse transformer
 - Suffers from complex voltage distribution, multiple switches, and large HV pulse transformer

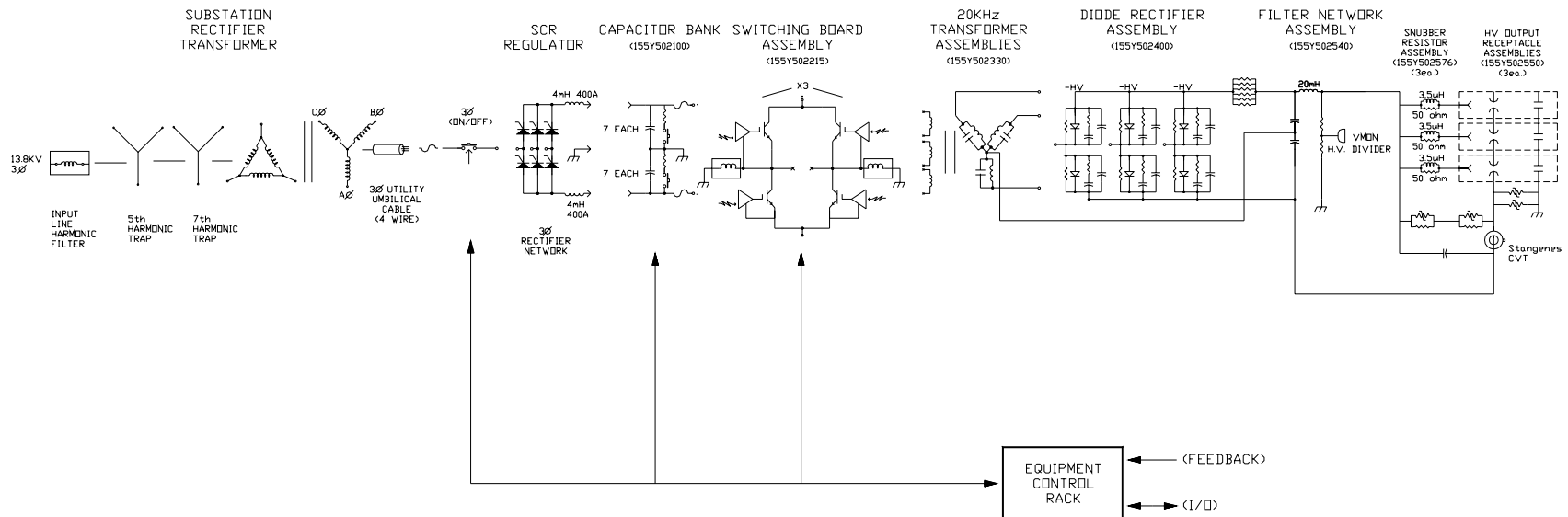
Existing IGBT Modulators -- TESLA



Simplified Block Diagram



- Design which utilizes high frequency switching capabilities of IGBTs
- Minimizes # of series IGBTs in switching sections
- Significantly reduces size of pulse transformer



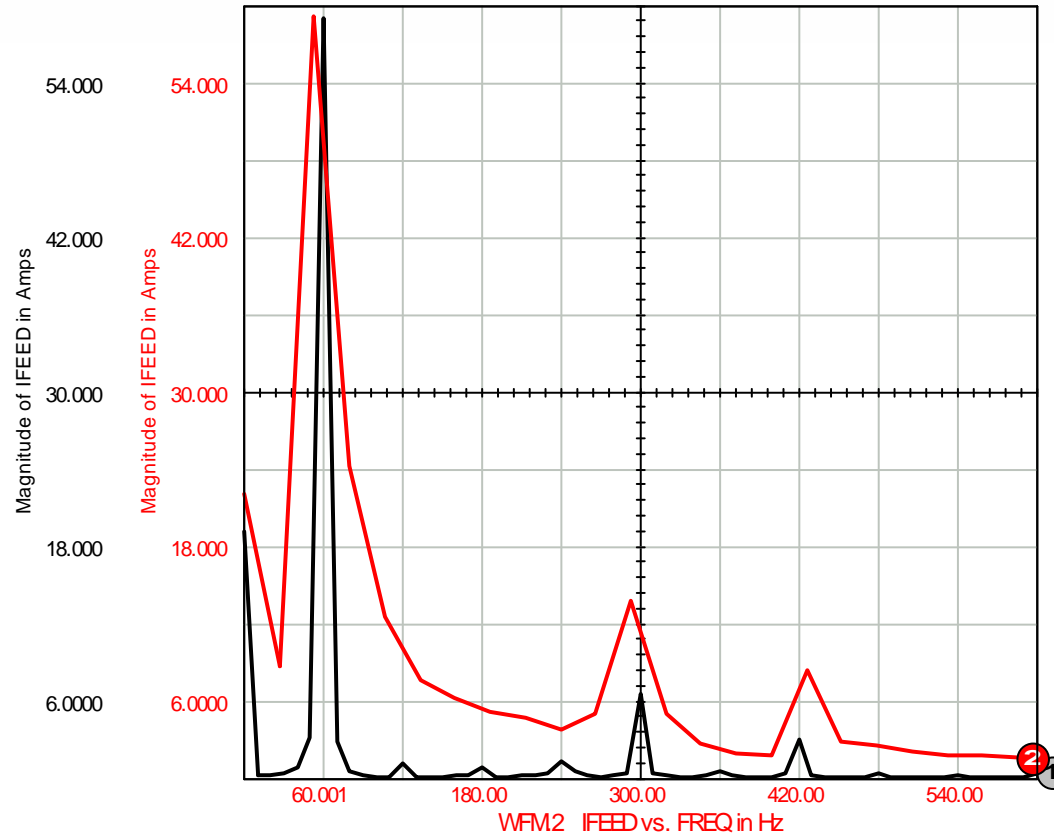
AC Power Management



- Use industry standard 13.8 kV : 2100 V 1.5 MVA transformer
 - ⇒ 2100 Vac distribution into bldg. straightforward
 - ⇒ ± 1250 V peak allows rectification with single device
 - ⇒ 3 phase system minimizes ripple and maximizes power delivered
 - ⇒ Dry type transformer eliminates environmental concerns, need for secondary oil confinement

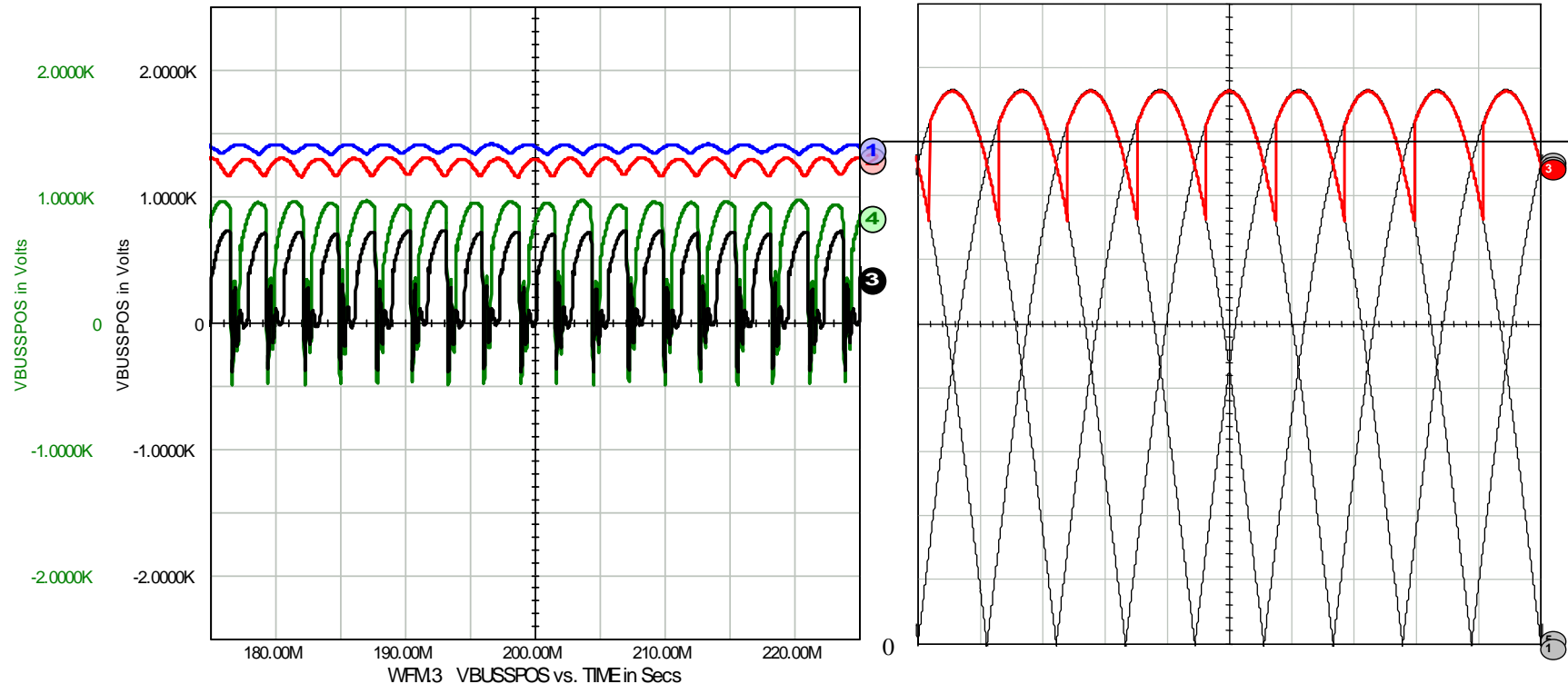


“Traps” Eliminate Harmonics



- 5th and 7th Harmonic Traps in Transformer
- Reduces harmonics by 2.3

3 phase SCR Controller Voltage



- Converts low voltage AC power into DC power
- Allows for “coarse” adjustment of voltage levels by varying conduction angles (shorter⇒higher voltage)
- Provides “knob” for DC voltage regulation
- Limits “in-rush” current at turn-on

Storage Capacitors & IGBT switches



- Self-clearing design protects hard-bussed units
- 110,000 μF per polarity is 160 kJ stored energy
- 20 years in service in traction motor industry w/o failure

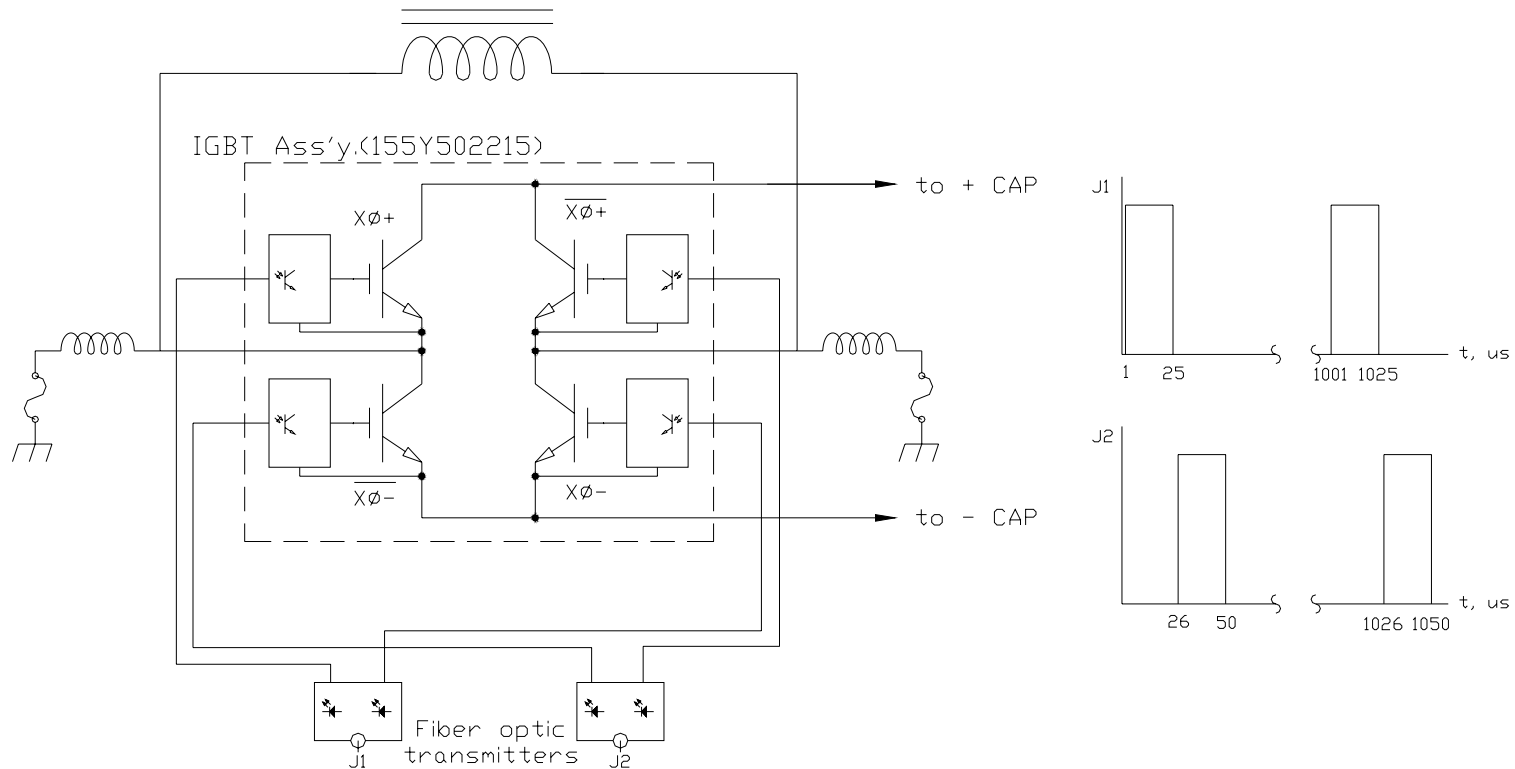


- Tradeoff between switching frequency (lower = smaller switching losses) and size of magnetics (lower = larger magnetics)
- 20 kHz H-bridge in 3 phases
- Pulse-width modulated

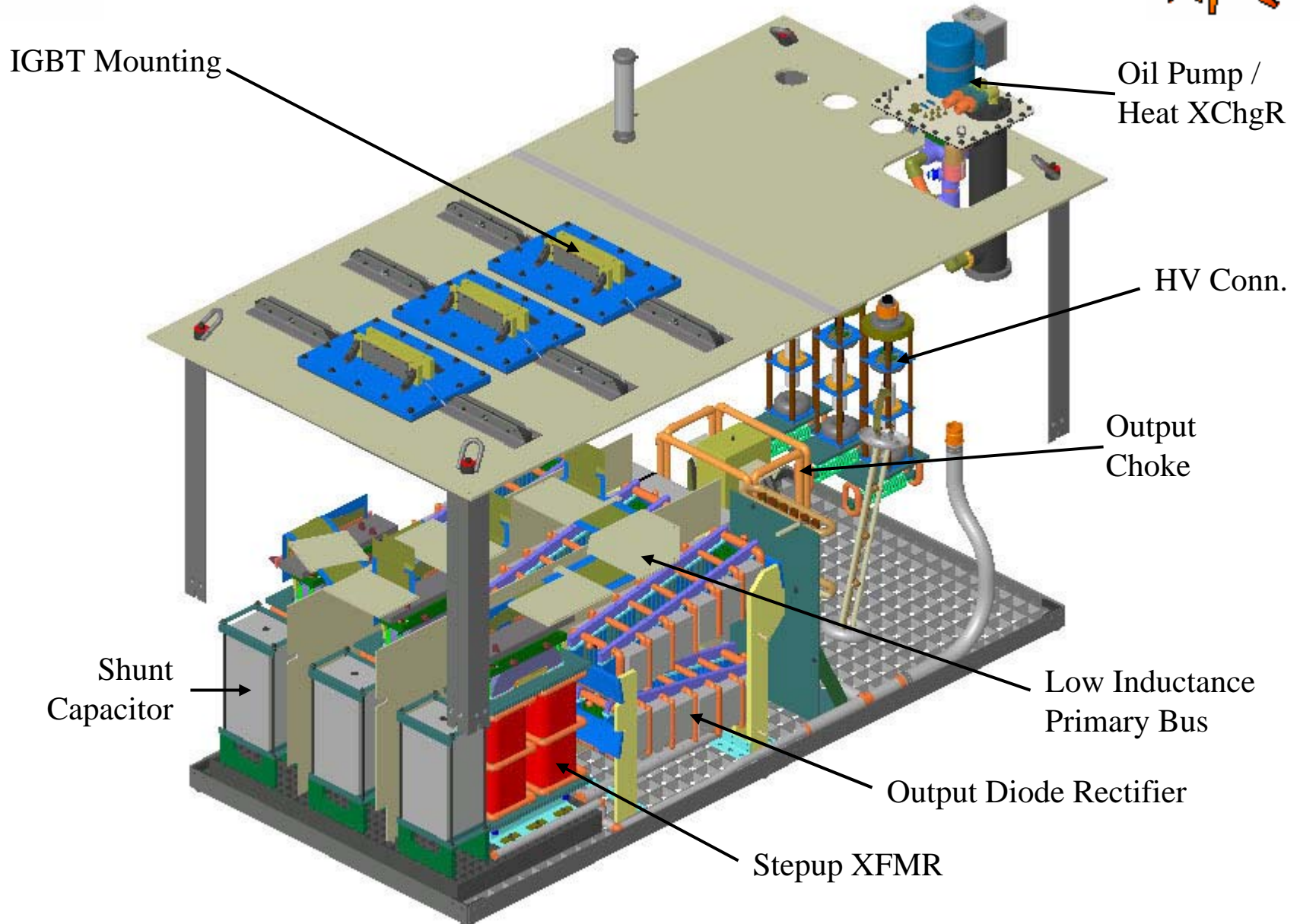
IGBT H-bridge



- Bipolar switching to simplify magnetics design
- Pulse Width Modulation (PWM) to control output voltage level and regulate output waveform
- 20 kHz operation results in switching losses (~5 kW/device)



Tank Basket Assembly



Boost Transformer / DC Rectifier



- 1:18 high voltage stepup transformer
 - ⇒ World's largest amorphous nanocrystalline cores
 - ⇒ ~300 W / pulse loss, order of magnitude below Metglas
 - ⇒ Combined with triple-resonant filter circuit to produce 1:47 voltage gain required for 140 kV pulses
- Series HV diodes for DC rectification
- Output filter <20 J of stored energy (minimizes damage from arcing klystrons) – 1 J measured @ 93 kV ⇒ 2.25 J @ 140 kV



Equipment Control Rack



Switchgear Remote Operator – keyed switch allows for remote open/close

SCR Control Head – not used for remote operation (displays active)

Power Distribution Panel

PanelView display – identical to EPICS screens

Control Chassis – controls IGBT gating and fast signals

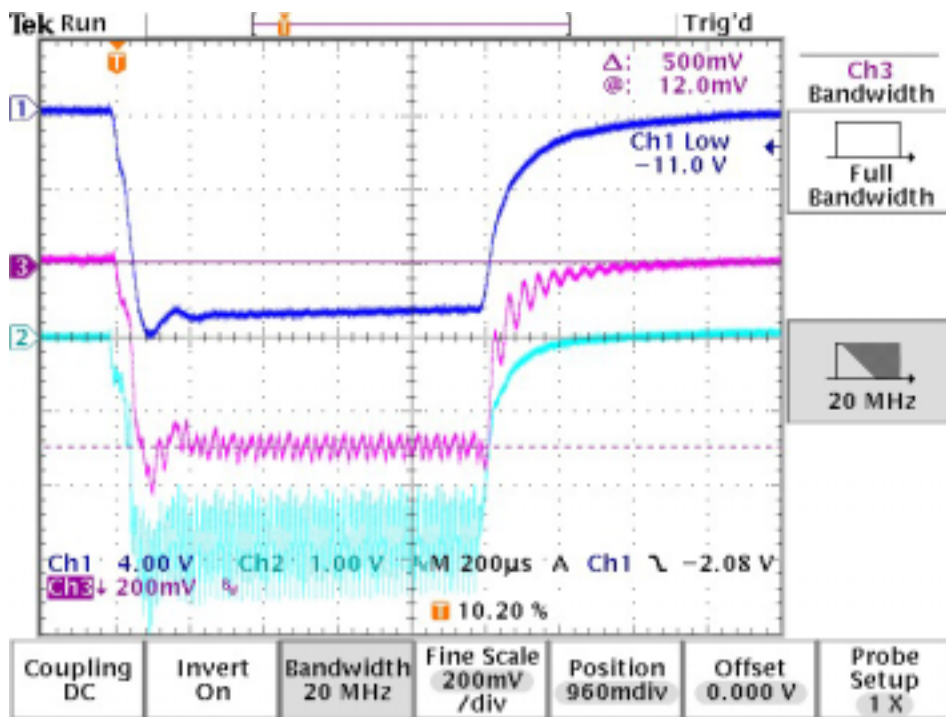
Interlock Chassis – manual reset of personnel faults and keyed

PLC Chassis

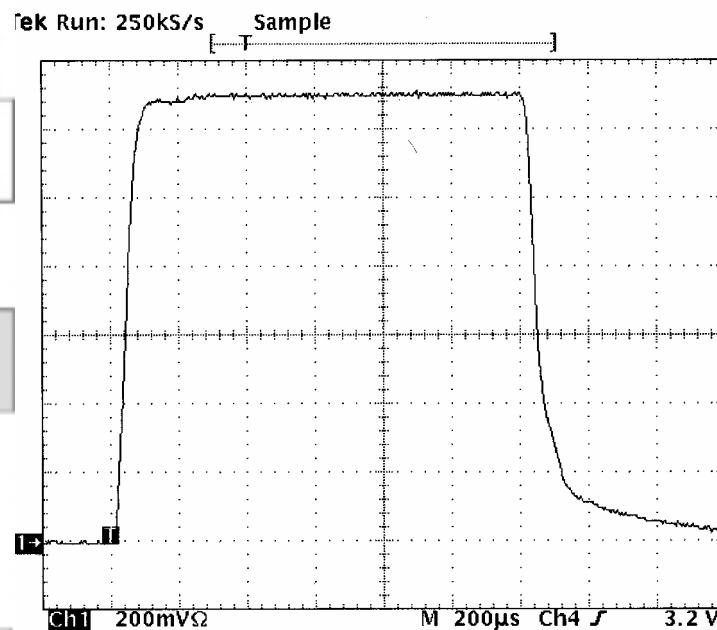
Demonstrated Output Waveforms



Step



1st -ORNL pulse



1st 80 kV pulse w/ feedback

13 Feb 2001
14:49:14

HVCM Hazards – all mitigated!



- Electrical – up to 150 kV pulsed, 1500 V dc
- Potential explosive energy release – from capacitors
- Thermal – Heating of IGBTs, other components under oil
- Insulating oil – potential for allergic reaction
- Trip / Fall – Cables, grounding bus, etc.
- Water pressure – 120 psi supply line
- Lifting / rigging – maintenance on tank components

Operators' Requirements



- Electrical Worker, LO/TO, CPR required
- OJT, including:
 - Training today
 - Demonstration of operations competency
- Emergency shut down procedures
- Maintenance personnel require additional OJT training

EMERGENCY PROCEDURES



- EVACUATE AREA IMMEDIATELY AND CALL 574-6606!
- IF POSSIBLE AND NO THREAT TO LIFE:
 - Push “EMERGENCY OFF” button on the front of the control rack OR SCRAM button in aisleway
 - Remove power feed to the system by opening the main circuit breaker
 - Remove 2100 V AC power from SCR unit by remotely opening switchgear

EMERGENCY NOTIFICATION LIST



- David Anderson Office: 241-7518 Cell: 300-5346
- Jim Hicks Office: 574-3180 Cell: 405-9689
- Ray Fuja Office: 241-6133 Cell: 405-6450

- In event of electrical accident:
 - Div/Group ESO: David Anderson Office: 241-7518
Home: 463-6746 Cell: 300-5346
 - Division Office: Norbert Holtkamp 241-6945
- Oil or water spill:
 - Facility Manager
- ASD Safety Representative: Sam McKenzie 241-8054

JHA / SOP Important Points



- Previous slides
- Authorized Worker Acknowledgement and Verification of HCP Review
- Modulator Start-Up Procedure Checklist
- Modulator Shutdown Procedure Checklist

- All Operators, Operator Support Personnel, and Maintenance Personnel must be listed.

- **Minimum of 2 people required for operation, checkout, testing, or maintenance of HVCM!**

Operating HVCM – All Screens



HPMod MAIN SCREEN, RFQ_HPRF EXIT

SETPOINT VOLTAGE MODULATOR <input type="text" value="50.0 kV"/>	MODULATOR VOLTAGE MONITOR 0.5 kV	MODULATOR CURRENT MONITOR 0.2 A		
SETPOINT CAP BANK VOLTAGE 0.000 kV <input type="text" value="0.900 kV"/>	+CAP BANK VOLTAGE MONITOR 0.004 kV	-CAP BANK VOLTAGE MONITOR 0.004 kV		
SETPOINT SCR BUS CURRENT LIMIT <input type="text" value="200.0 A"/>	+SCR BUS CURRENT MONITOR 0.5 A	-SCR BUS CURRENT MONITOR 0.4 A		
CAP BANK VOLT. ALG. CONTROL <input type="text" value="ON/OFF"/>	CAP BANK VOLT. STATUS OFF	CAP BANK VOLT. STATUS In Range	STANDBY TIMEOUT 0	STANDBY COOL DOWN 0
OPERATION STATE Rack Stby	OPERATION MODE Remote	EQUIPMENT FAULT FAULT	PERSONNEL FAULT OK	SCREEN SELECTOR HPMod
RACK CONTROL				
<input type="text" value="OFF"/> <input type="text" value="STANDBY"/> <input type="text" value="RUN"/> <input type="text" value="FLT RESET"/>				

- Oper. State
 - Off
 - Standby
 - Run
- Oper. Mode
- Equip. Fault
 - Reset with Flt Reset button
- Personnel Fault
 - Reset locally only
- Screen Selector

Operating HVCM – Main Screen



HPMod MAIN SCREEN, RFQ_HPRF EXIT

SETPOINT VOLTAGE MODULATOR 50.0 kV	MODULATOR VOLTAGE MONITOR 0.5 kV	MODULATOR CURRENT MONITOR 0.2 A
SETPOINT CAP BANK VOLTAGE 0.000 kV 0.900 kV	+CAP BANK VOLTAGE MONITOR 0.004 kV	-CAP BANK VOLTAGE MONITOR 0.004 kV
SETPOINT SCR BUS CURRENT LIMIT 200.0 A	+SCR BUS CURRENT MONITOR 0.5 A	-SCR BUS CURRENT MONITOR 0.4 A

CAP BANK VOLT. ALG. CONTROL ON/OFF	CAP BANK VOLT. STATUS OFF	CAP BANK VOLT. STATUS In Range	STANDBY TIMEOUT 0	STANDBY COOL DOWN 0
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OPERATION STATE Back Stby	OPERATION MODE Remote	EQUIPMENT FAULT FAULT	PERSONNEL FAULT OK	SCREEN SELECTOR HPMod
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RACK CONTROL

OFF	STANDBY	RUN	FLT RESET
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- Setpoints in green open-loop, blue closed-loop
- Cap Bank V Algorithm for future use
- SCR Bus Current and Cap Bank V (X2) determine average power

Operating HVCM – Analog Setup



HPMod Analog Setup & Status Screen

HPMod ANALOG SETUP & STATUS SCREEN, RFQ_HPRF

EXIT

SETPOINTS		MONITORS	
CAP BANK OVER-VOLTAGE THRESHOLD	CAP BANK DIFF VOLTAGE THRESHOLD	+SCR BUS VOLTAGE MONITOR	-SCR BUS VOLTAGE MONITOR
1.300 kV	0.300 kV	0.000 kV	0.026 kV
SCR BUS OVER-CURRENT THRESHOLD	SCR LINE OVER-VOLTAGE THRESHOLD	SCR LINE 1 VOLTAGE MONITOR	SCR LINE 1 CURRENT MONITOR
500.0 A	2.600 kV	0.001 kV	0.0 A
SCR LINE OVER-CURRENT THRESHOLD	MOD VOLTAGE ADMIN LIMIT	SCR LINE 2 CURRENT MONITOR	SCR LINE 3 CURRENT MONITOR
500.0 A	150.0 kV	0.1 A	0.1 A
SCR CURRENT ADMIN LIMIT	SCR VOLTAGE ADMIN LIMIT		
500.0 A	1.950 kV		

OPERATION STATE	OPERATION MODE	EQUIPMENT FAULT	PERSONNEL FAULT	SCREEN SELECTOR
Back Stby	Remote	FAULT	OK	HPMod

RACK CONTROL

OFF	STANDBY	RUN	FLT RESET
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- Controls for administrative limits – must be set locally!
- Monitors may be useful for troubleshooting

Operating HVCM – Equipment Status



HPMod Equipment Status Screen

HPMod EQUIPMENT STATUS SCREEN, RFQ_HPRF

EXIT

CNTRL CHASSIS SCR INHIBIT	EPS BYPASS SWITCH MON	XMTR1 BYPASS SWITCH MON	XMTR2 BYPASS SWITCH MON	XMTR3 BYPASS SWITCH MON
INHIBIT	BYPASS	ENABLE	BYPASS	BYPASS
CNTRL CHASSIS SWITCH MON	+CAP BANK A DUMP RELAY	+CAP BANK B DUMP RELAY	-CAP BANK A DUMP RELAY	-CAP BANK B DUMP RELAY
SETUP	CLOSED	CLOSED	CLOSED	CLOSED
CNTRL CHASSIS SPARE STS	SCR CAB AC POWER	SCR PWR SUPPLY	SCR OPERATE	SCR CURRENT LIMIT
CLOSED	CLOSED	NOT RDY	REMOTE	NOT LIMITING
CNTRL CHASSIS SPARE INHIBIT	IGBT DRVRBD AC POWER	OIL PUMP AC POWER	OIL HEATER AC POWER	
INHIBIT	CLOSED	CLOSED	OPEN	

OPERATION STATE	OPERATION MODE	EQUIPMENT FAULT	PERSONNEL FAULT	SCREEN SELECTOR
Rack Stby	Remote	FAULT	OK	HPMod

RACK CONTROL

OFF	STANDBY	RUN	FLT RESET
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- Verifies if bypasses are enabled
- Verifies Dump Relay status
- Verifies SCR and power distribution status

Operating HVCM – Equipment Fault



HPMod Equipment Fault Screen

HPMod EQUIPMENT FAULT SCREEN, RFQ_HPRF

EXIT

XMTR1 RUN PERMIT	XMTR2 RUN PERMIT	XMTR3 RUN PERMIT	EPS RUN PERMIT	GATE IN PLS WID	MOD OUT PLS WID	PULSE REP INT
DUTY CYCLE	INTER PULSE	IGBT OI A+	IGBT OI A-	IGBT OI B+	IGBT OI B-	IGBT OI C+
IGBT OI C-	IGBT OI *A+	IGBT OI *A-	IGBT OI *B+	IGBT OI *B-	IGBT OI *C+	IGBT OI *C-
IGBT FLT A+	IGBT FLT A-	IGBT FLT B+	IGBT FLT B-	IGBT FLT C+	IGBT FLT C-	IGBT FLT *A+
IGBT FLT *A-	IGBT FLT *B+	IGBT FLT *B-	IGBT FLT *C+	IGBT FLT *C-	MOD OV	MOD OI
DSP FAULT	CNTRL PPS SUM	CNTRL EPS SUM	WP EPS1	WP EPS2	WP OIL HIGH	XMTR1 EPS
XMTR2 EPS	XMTR3 EPS	TPS FAULT	SCR LOW H2O	SCR HI TEMP	DUMP RELAYS	+CAP BANK OV
-CAP BANK OV	+SCR BUS OV	-SCR BUS OV	CAP BANK DIF V	SCR BUS DIF V	+SCR BUS OI	-SCR BUS OI
SCR LINE 1 OV	SCR LINE1 OI	SCR LINE2 OI	SCR LINE3 OI	EPICS FAULT	SCR LOCAL FAULT	

OPERATION STATE	OPERATION MODE	EQUIPMENT FAULT	PERSONNEL FAULT	SCREEN SELECTOR	EPICS FAULT TIMER SET- POINT (msec)
Rack Stby	Remote	FAULT	OK	HPMod	20000

RACK CONTROL

PLC HEALTH

- Most useful screen for troubleshooting
- All green (except Dump Relays) during operation
- Corresponds to troubleshooting table

Operating HVCM Fault Troubleshooting Table



- XMTRn RUN PERMIT – Transmitter crowbarred HVCM, check transmitter
- EPS RUN PERMIT – MPS inhibited HVCM, check MPS log
- GATE IN PLS WID – Incoming gate pulse width >1.5 ms, check timing module or setting
- MOD OUT PLS WID – Voltage readback pulse width too wide, check cable connection and/or klystron connection
- PULSE REP INT – Rep rate >60 Hz, check timing module or setting
- DUTY CYCLE – Duty cycle > setpoint, check timing module or setting
- INTER PULSE – Voltage present on readback outside of gate pulse, check cable connection and/or klystron connection
- IGBT OI n+/- – IGBT currents exceed threshold setpoint. If fault reoccurring, contact HVCM tech. or engineer
- MOD OV – Modulator voltage exceeds setpoint in closed loop mode, adjust on Main Screen or possible fault due to klystron not conducting current
- MOD OI – Modulator current exceeds setpoint, adjust on Analog Status & Setup Screen (requires HVCM tech. or engineer) or fault due to klystron or internal arcing.
- DSP FAULT – DSP in control chassis faulted, contact HVCM tech. or engineer
- CNTRL PPS SUM – PPS fault, requires local reset (consult Personnel Fault Screen)
- CNTRL EPS SUM – Equipment fault, reset remotely (consult Equipment Fault Screen)
- WP EPSn – Water panel ‘auxiliary fault, presently hardwired.

Operating HVCM Fault Troubleshooting Table



- WP OIL HIGH – Oil level too high, probably due to heating. Contact HVCM tech. or engineer
- XMTRn EPS – Transmitter equipment protection fault, check transmitter screen
- TPS FAULT – Target protection system fault (presently not installed)
- SCR LOW H2O – Low water flow in SCR unit, check valves and call HVCM tech. or engineer if doesn't clear
- SCR HI TEMP – Water return temperature too high, check supply temperature and call HVCM tech. or engineer if fault doesn't clear
- DUMP RELAYS – Dump relays status
- +/-CAP BANK OV – Voltage exceeds setpoint, adjust on Main Screen
- +/-SCR BUS OV – Voltage exceeds setpoint, adjust on Analog Status & Setup Screen
- CAP BANK DIF V – Voltage imbalance. Try again and contact HVCM tech. or engineer if fault doesn't clear
- SCR BUS DIF V – ditto above
- +/-SCR OI – SCR DC current too high. Adjust setting on Analog Status & Setup Screen
- SCR LINE n OV – SCR AC current too high. Adjust setting on Analog Status & Setup Screen
- EPICS FAULT – self-explanatory
- SCR LOCAL FAULT – Fault in SCR control head. Reset, try again, and contact HVCM tech. or engineer if fault doesn't clear

Operating HVCM – Personnel Protect Fault



- Faults jeopardizing personnel safety
- Must be reset locally at Interlock Chassis!

Operating HVCM – Alarm History



HPMod Alarm History Screen

Clear List HPMod ALARM HISTORY SCREEN, RFQ_HPRF EXIT

1/23/02 12:41:42.446	Pulse Repetition Interval Fault
1/23/02 12:41:42.446	IGBT 1C- Phase Fault
1/23/02 12:41:42.446	Transmitter 2 Run Permit Fault
1/23/02 12:41:42.546	PPS Interlock Sum (All OK)
1/23/02 12:41:42.546	Crit Chassis PPS Sum Input Fault
1/23/02 12:41:42.746	IGBT 1B- Phase Fault
1/23/02 12:41:42.846	IGBT B- Phase Over-Current
1/23/02 12:41:42.846	IGBT A- Phase Over-Current
1/23/02 12:41:43.046	SCR Low Water Flow Fault
1/23/02 12:41:43.146	IGBT 1C- Phase Over-Current
1/23/02 12:41:43.246	IGBT 1A- Phase Fault
1/23/02 12:41:43.346	Modulator Over-Current Fault
1/23/02 12:41:43.446	Transmitter 1 Run Permit Fault
1/23/02 12:41:43.546	Cap Bank Dump Relay Fault
1/23/02 12:44:05.764	IGBT 1A- Phase Over-Current
1/23/02 12:44:05.864	Crit Chassis EPS Sum Input Fault
1/23/02 12:44:05.964	EPS Sum Fault
1/23/02 12:48:12.064	Cap Bank Dump Relay Fault
1/23/02 11:01:17.064	Transmitter 1 Run Permit Fault
1/23/02 11:01:17.464	Crit Chassis EPS Sum Input Fault
1/23/02 11:01:17.564	EPS Sum Fault
1/23/02 12:53:57.264	Cap Bank Dump Relay Fault
1/23/02 14:24:51.364	Transmitter 1 Run Permit Fault
1/23/02 14:24:51.464	Crit Chassis EPS Sum Input Fault
1/23/02 14:24:51.564	EPS Sum Fault

OPERATION STATE	OPERATION MODE	EQUIPMENT FAULT	PERSONNEL FAULT	SCREEN SELECTOR
Back 58by	Remote	FAULT	OK	HPMod

RACK CONTROL

OFF	STANDBY	RUN	FLT RESET
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- Useful for troubleshooting
- Logs all faults in order